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Adaptation strategies of agriculture and water management to climate change in the Upper Tarim River basin, NW China

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ABSTRACT

The Upper Tarim River basin, contributing about 85% of the total inflow to the mainstream Tarim River, is heavily influenced by climate change and human interferences. This study is the first integrated assessment of agriculture and water management under climate change scenarios for this arid river basin in Central Asia. It aims to analyze changes in river discharge of the Upper Tarim under 28 climate projections for 3 representative concentration pathways (RCP) and the A1B scenario and 30 combinations of changes in land use (agricultural area) and water saving measures considered as adaptation strategies. Headwater discharge simulations of two hydrological models (SWIM-G and WASA) are used to drive a hydrological model of the lowland area (SWIM-oasis), taking account irrigation and river transmission losses. The projections show that the river discharge of the Upper Tarim River is likely to increase in a warmer climate if the agricultural area is reduced to the level as in 1998 even without any water saving measures. If the agricultural area increases to the 2010 level, strong water saving measures must be applied to ensure sufficient water inflow to the mainstream Tarim under all climate scenarios. If agricultural area continues to expand, there is a risk of decreasing river discharge at the end of this century under the RCP2.6 scenario. The uncertainty of the projections is large, especially in the far future, and it is mainly related to the climate and hydrological models.

1. Introduction

Within the climate change research community, increasing attention has been given to adaptation to a changing climate (Arnell, 2010). However, it is still less common to assess the consequences of land use change, adapted water management and climate scenarios together. In addition, most adaptation studies (Kirby et al., 2014; Kling et al., 2014; Tu, 2009) assessed the impacts of potential changes and only a few studies specifically addressed the actual or planned adaptation measures to cope with climate change impacts (Arnell, 2010). One of the few examples is the combined bottom-up and top-down assessment of climate change adaptation by Bhave et al. (2014), who selected three adaptation options prioritized by stakeholders and projected impacts on streamflow under four climate projections for the Kangsabati River catchment in India.

These adaptation studies reported in literature usually consider a small number of land use change or management scenarios, and each climate scenario is combined with only one change in either land use or management. A combination of different land use and management options is rare in climate impact assessments. Applications and comparisons of modelling results from more than one impact model are also rare in climate adaptation analysis. However, the uncertainty related to impact models, e.g. hydrological models, can be comparable to that related to climate models for some specific basins (Velazquez et al., 2013; Vetter et al., 2015), though most often the latter dominates (Vetter et al., 2016). Since water planning and operation decisions are affected by large uncertainties related to both climate scenarios and impact models, climate adaptation studies should examine not only various climate scenarios but also the application of several impact models to evaluate uncertainty and to produce robust results.

Central Asia is highly vulnerable to water scarcity due to the arid climate and intensive irrigated agriculture. Attention has already been

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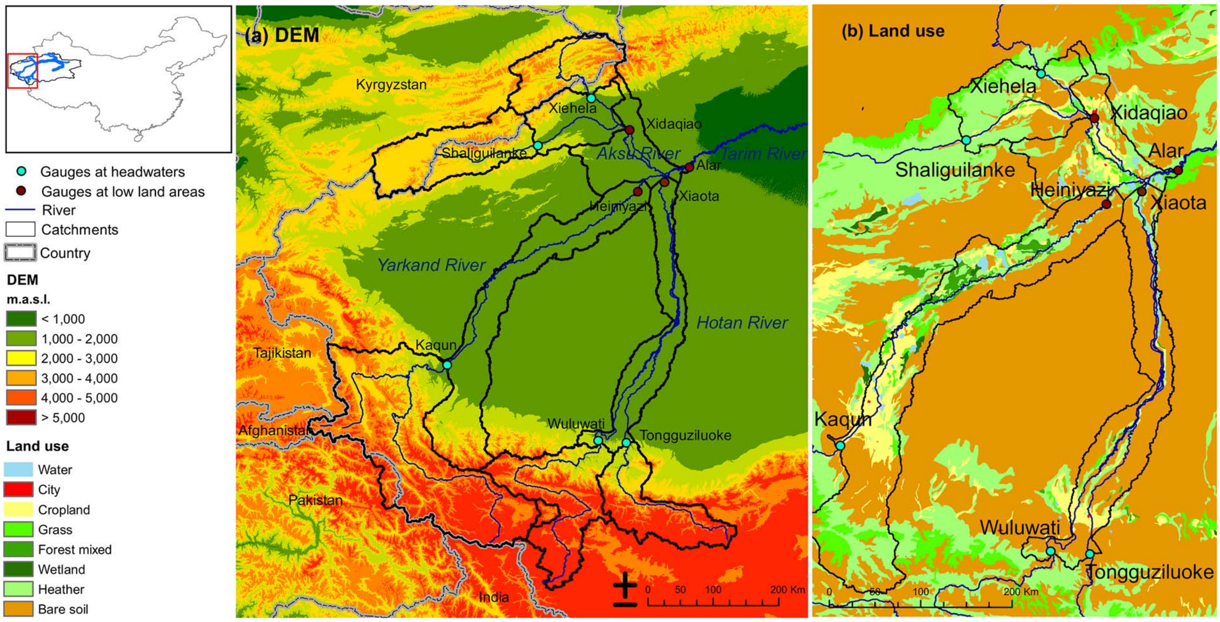

Fig. 1. The digital elevation model (DEM) of the Upper Tarim basin (a) and the land use between the five headwater gauges and Alar, i.e. the lowland area (b).

paid to the vulnerability to climate change and the adaptation measures in this region (Aleksandrova et al., 2014). The Tarim River is the largest endorheic river in China. It receives water from four mountainous tributaries (the Aksu, Hotan Yarkand and Kaidu rivers) and dries up in the Taklamakan Desert. The length of the river decreased by about 770 km (about 35% of the total length) from 1990s to 2009, mainly due to the intensive irrigation and increased population in the river oases along the tributaries and the mainstream Tarim River (Chen et al., 2009). Consequently the whole oasis ecosystem of the Tarim was adversely affected by the strong decrease in river runoff downstream (Xu et al., 2008).

The project SuMaRio (Sustainable Management of River Oases along the Tarim River/China, http://www.sumario.de/, 2011–2016, funded by the German Ministry for Education and Research), aimed to find a sustainable development strategy for the Tarim River region that would maintain both ecosystem services and economic benefits (Rumbaur et al., 2015). To achieve this goal, the first question to answer is how much water would be available for the Tarim River oases in the future accounting for climate change, agriculture and water management options. As the upper three tributaries (Aksu, Hotan and Yarkand) contribute about 85% of the total water inflow to the Tarim River (Gou et al., 2010), the future discharge from these tributaries is a key factor to determine the total water availability in the mainstream.

Despite the importance of analyzing the future water resources in the Tarim River, studies focusing on this topic for the region are limited. Several published studies analyzed the historical trends, changes and impacts for the Tarim River or its tributaries (Fu et al., 2012; Krysanova et al., 2015; Xu et al., 2013). Recently, Keilholz et al. (2015) projected the impacts of climate and land use changes on groundwater in a middle reach of the Tarim River. Fang et al. (2015) projected the impacts of climate change on streamflow of the Kaidu River. Yu et al. (2015) analyzed the impacts of irrigation and water saving measures on discharge in the main Tarim River in the period 2006–2008. Specifically for the Upper Tarim, Liu et al. (2013) projected changes in runoff using a distributed macro-scale hydrological model under the A1B, A2 and B1 scenarios. However, their modeling didn't consider any glacier changes in the headwaters or water uses in the lowland area. A more advanced hydrological modeling was presented by Duethmann et al. (2016), who investigated impacts of climate change on glaciers and discharge in headwater catchments of the Aksu River, using an ensemble of different emission scenarios, climate models, and parameters of the hydrological model. To our best knowledge, none of the previous studies could provide a robust projection on streamflow for the entire Upper Tarim, including both agricultural water use and climate impacts in the assessment.

To fill this gap, our study is the first comprehensive climate impact and adaptation assessment on the water availability at the Alar station, the last gauge station of the Upper Tarim River, based on a large number of climate, agricultural and water management scenarios including the real planned measures. For simplicity, we will use "agricultural scenarios" instead of "agricultural and water management scenarios" as a short term in the following text. In addition, we applied simulation results from two glaciohydrological models for headwaters to investigate the uncertainty related to hydrological models. The main objectives of this study are: 1) to project river discharge of the Upper Tarim River at the Alar station under various climate projections; 2) to quantify the effects of various agricultural scenarios in combination with climate change on discharge; 3) to find robust adaptation measures for the near, medium and far future, and 4) to analyze the uncertainty of projected impacts related to the climate models, hydrological models and agricultural scenarios.

2. Study area

The Tarim River basin is mainly located in the northwest of China with parts of the headwater areas in Kyrgyzstan and Pakistan. The mainstream of the Tarim River begins at the confluence of three tributaries – the Aksu, Yarkand and Hotan rivers (Fig. 1a). The hydrologically active catchment area (i.e. without endorheic lakes and rivers not reaching the mainstream) until the Alar station is defined here as the Upper Tarim basin, with a total drainage area of 184,567 km^2.

The Upper Tarim River can be divided into two parts according to different topographic, climatic and hydrological conditions: the five headwaters in the mountains until the gauges Xiehela, Shaliguilanke, Kaqun, Wuluwati and Tongguziluoke, and the lowland area between the headwater stations and the Alar station in the Taklamakan Desert (Fig. 1a). The headwaters of the three tributaries are mainly fed by snow and glacier melting in the mountains and are hardly influenced by human activities. The headwaters of the Aksu River have the largest discharge at 255.6 m^3/s on average (in the period from 1957 to 2005), while the headwaters of the Yarkand and the Hotan rivers provide smaller amount of water resources, 208.6 and 142.8 m^3/s on average

(Xie et al., 2007).

In the lowland area, there is little water generation due to extremely low rainfall (30–60 mm/year) and high potential evaporation (2000–3000 mm/year) (Xu et al., 2008). Bare soil is the dominant land cover type, but there are large oases along the rivers covered by irrigated cropland, forest and grassland. The irrigation water is important not only for agriculture but also for the whole oasis ecosystem. All natural vegetation depends on groundwater, which is recharged by seepage from streams, water delivery canals and irrigated fields (Zhong et al., 2009). Hence, a large amount of irrigation water is used by both crops and natural vegetation in the oases. In addition, so-called river transmission losses, i.e. evaporation and percolation in rivers, are important processes, especially for rivers in arid regions (Hughes 2008). As a result, the water use in oases and river transmission losses lead to a reduction of river discharge between the headwaters and the Alar station downstream.

The inflows from the Hotan and Yarkand rivers to the Tarim are gauged by the stations Xiaota and Heiniyazi near the outlet of these rivers, respectively. For the Aksu River, no discharge data is available at the outlet for this study. However, the gauge station Xidaqiao provides the discharge information at the confluence of the two headwaters (Toshkan and Kumarik Rivers). As the most upstream gauge of the Tarim River, the Alar station monitors the inflow of all three tributaries, i.e. the available water amounts entering the main Tarim River, which this study focuses on.

In the past 53 years (1957–2009), the average inflow to the Tarim River was about 140 m^3/s, including 73% water from the Aksu, 24% from the Hotan and 3% from the Yarkand (Gou et al., 2010). Due to large river transmission losses and water use in the oases, only the Aksu River maintains a permanent inflow to the Tarim River. The Hotan River contributes to the Tarim only during the flooding season (July–September). Regarding the Yarkand River, there was no water runoff into the Tarim River since 1985, except during two extreme floods in 1994 and 2005. The 270 km river reach downstream is dry for most years.

The total annual streamflow from all headwater stations tended to increase in the period 1956–2009 (see Appendix A). The increase is mainly due to the increase of discharge in the Aksu headwaters, and this is explained by climatic changes (Duethmann et al., 2016). Despite the increasing trend in the headwater flow, the annual streamflow at the Alar station shows a decreasing trend, indicating an increasing trend of water use in the oases, mainly due to the increasing water demand for the expansion of irrigated area in this region (Deng et al., 2013).

Since the headwaters and the lowland area are so different in terms of hydrological processes and human influences, we divided our model domain into two parts: 1) headwater regions modelled by two glacio-hydrological models; and 2) the lowland area modelled by one hydrological model considering irrigation water use and river transmission loss. Simulation results for the headwater regions are shown in Wortmann (2017) and Duethmann et al. (2016). Using the simulated headwater discharge as input, this study focuses on the lowland area and projects the discharge at the Alar station as the water availability from the entire Upper Tarim basin.

2.1. The agricultural conditions in the lowland area

The agricultural water use is the major focus of this study. Abstractions in this sector account for about 95% of the total water use in the Tarim River Basin.

In order to understand the recent historical agricultural changes in the lowland areas, we analyzed data from the following statistical yearbooks: the Xinjiang Statistical Yearbooks (XJSYB, 1990–2012) for local counties and the Bingtuan Statistical Yearbooks (BTSYB, 1990–2012) for the Agricultural Divisions from the Xinjiang Production and Construction Corps from 1989 to 2011. Fig. 2 shows the historical development of the total cultivated area including cropland, forest and orchard (a), and the distribution of crops (b–d) in the oases of three tributary basins.

In general, the total cultivated area was increasing continuously in the recent 20 years, and the expansion became drastic between 2004 and 2009 in the Aksu and Yarkand river basins. The increase in area is a result of population growth, increase in agricultural profitability, the local afforestation programs pushing for the establishment of orchards, and insufficient restriction measures of agricultural land expansion (Feike et al., 2015).

The distribution of crops is different among these three river basins. In the Asku basin, cotton is the dominant crop, accounting for about 50% of the total agricultural area since 2000. In the Hotan basin, winter wheat and maize are the main crops, and their areas are relatively constant after 2000. In the Yarkand River basin, cotton, winter wheat and maize are the dominant crops, covering 60–80% of the total area. Rice, which requires more water compared to other crops, is mainly planted in the Aksu basin, and its area gradually declined in the last decade. An increasing trend of the forest and orchard areas is found in all three river basins, especially after 2000, due to the local afforestation programs.

2.2. Irrigation practices

According to Zhong et al. (2009), surface irrigation is still the most widespread and important method, accounting for over 80% of the irrigation area in the Xinjiang province. However, the areas using water saving irrigation technologies (e.g. drip irrigation, spray irrigation and low-pressure pipeline delivery irrigation) increased rapidly over the last decade. The drip irrigation is the most popular water saving technology, applied in 64% of the total water saving irrigation area in Xinjiang by the end of 2004. Water is mainly delivered through canals from rivers to farmland. However, the water seepage in traditional canals is very high, accounting for 50–60% of the total water withdrawal. In canals with sandy soils, the seepage can be as high as 70%. As a result, the conventional irrigation efficiency (CIE), which is defined as the efficiency of the total process of irrigation from the source of water to the point where the water becomes available in the root zone of plants (Merwe et al., 1997), is rather low, ranging from 0.3 to 0.5, depending on region. In general, the CIE in the Aksu basin is higher than in the other two basins.

In order to avoid waste of water and enhance the irrigation management, each county in the Aksu basin and the Agricultural Division set up an irrigation instruction, regulating the irrigation schedule and quotas (Wang, 2006). These instructions consider that irrigation is required not only during the main growing season (May to September), but also during winter and early spring to achieve salt leaching and soil moisture conservation.

For example, the instruction for the Awati County lists the irrigation schedule and quotas for winter wheat, maize, rice, cotton with surface irrigation, cotton with drip irrigation, beet, oil plant, other economic plants, orchard, vegetables, forest and grassland. As the dominant and important crop, cotton should be irrigated five times a year. The five irrigation periods are 20th Feb.–10th Mar. (before sowing), 11th Jun.–20th Jun. (squaring stage), 11th Jul.–21th Jul. (flowering stage), 10th Aug–20th Aug (boll stage) and 25th Aug.–5th Sep. (boll opening stage), with irrigation quotas of 1200, 975, 975, 975, 975 m^3/ha, respectively. In total, 5100 m^3 water is needed to irrigate one hectare of cotton per year. For cotton with drip irrigation, there are twelve irrigation periods in total, including one irrigation before sowing of 1350 m^3/ha in March, and eleven irrigations of 300 m^3/ha each during the growing season. Compared to the surface irrigation for cotton, the drip irrigation requires longer irrigation duration but less water per day. For winter wheat, one summer irrigation (from August to September) and one autumn irrigation (from October to November) are required before the crop starts to grow. The total irrigation quota per

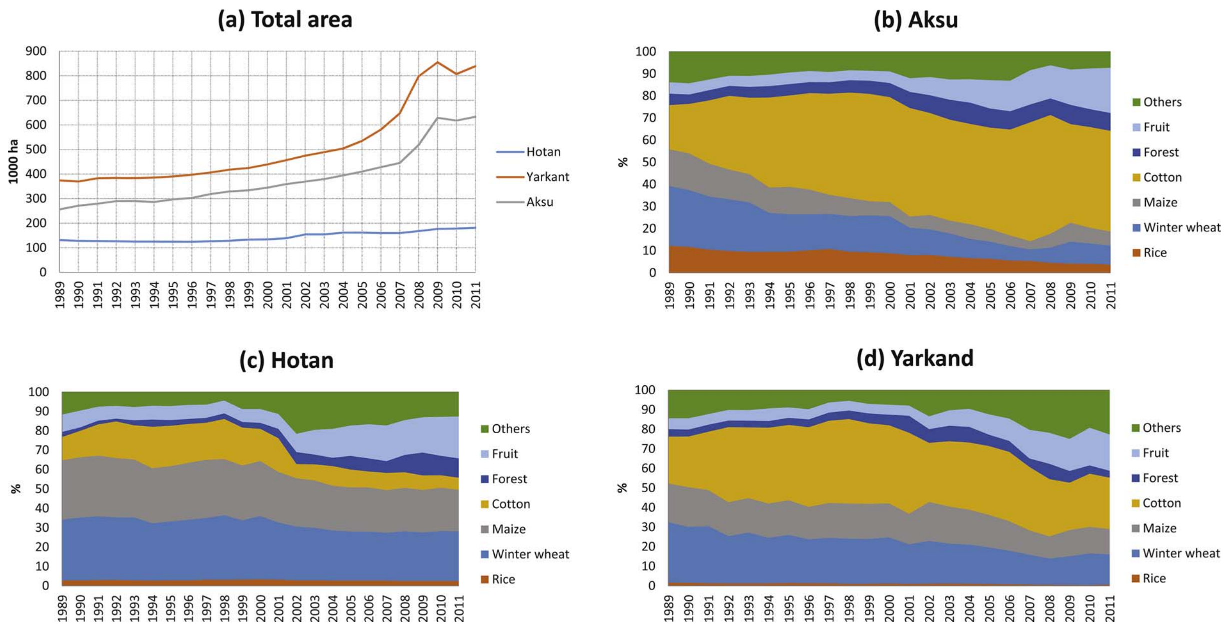

Fig. 2. Historical development of cultivated area (a) and the composition of crop types in each river basin (b–d) from 1989 to 2011.

year ranges from 4500 to 6000 m^3/ha for all crops except for rice, which requires 13500 m^3/ha. Note that the irrigation quota in the instruction refer only to water that reaches the root zone of crop. Taking into account the low CIE in the three basins, the average irrigation water demands are around 11 300 $m^3\,ha^{-1}$ and 14 300 $m^3\,ha^{-1}$ in the North and South Xinjiang, respectively (Deng, 2010).

2.3. The governmental plan for the Tarim River basin

In 2001, the government of the Xinjiang Uygur Autonomous Region (GXUAR) and the Ministry of Water Resources of P.R. China (MWRC) approved “A planning report for immediate comprehensive improvement to the Tarim River Basin” (GXUAR and MWRC, 2002). This plan aims to ensure the ecological water demand in the main Tarim River until 2010 by adopting a quota system to fix the water use in the three tributaries and between the upper, middle, and lower reaches of the Tarim River. Specifically for our study area, the Tarim River at the Alar station should receive 4.6 billion m^3/year (ca. 146 m^3/s) under average climatic conditions according to this plan. This represents the median streamflow for the historical discharge from 1957 to 1998. To achieve this goal, different measures were carried out, such as improvements of the transportation canals, use of water saving irrigation technologies, restriction of agricultural area to the field area from 1998, construction of reservoirs in the headwaters, increase in groundwater exploration, and restoration of the main Tarim River bed (Thevs, 2011).

However, the objective of the plan could not be achieved until 2010. The average water flow at Alar decreased by about 26 m^3/s in the period from 2001 to 2009, while the average inflow from the five headwaters increased by about 86 m^3/s compared to the average inflow amount in the last 50 years. Hence, Liu et al. (2010) suggested to restrict the expansion of irrigated area in the three tributary basins, and to restore the Hotan and Yarkand river beds downstream. In their opinion, it is only viable to increase the irrigated area in the Hotan basin, while the irrigated areas in the other two basins should be reduced to the level of 1998.

3. Methods and data

Fig. 3 shows the flowchart of the models as well as the major input data. This study uses results of two glaciohydrological models simulating the five highly glacier covered headwaters as input. The models and their results are briefly described in Section 3.1 with more detailed presentations given in Duethmann et al. (2016) and Wortmann (2017). The two headwater models enable us to account for the uncertainty introduced by glaciohydrological impact models. The lowland area was simulated by the model SWIM-oasis (Section 3.2) and is calibrated using the same reference data (WATCH and APHRODITE) as the two headwater models. The same climate scenarios were used in both headwater models and the lowland model. Section 3.3 presents how water use was calculated based on the irrigation instructions for agricultural scenarios. The uncertainty sources were quantified using the ANOVA method (Section 3.4), and the input data are introduced in Sections 3.5–3.7.

3.1. The headwater modelling

The results of two glaciohydrological models, WASA (Water Availability in Semi-Arid Environments) and SWIM-G (Soil and Water Integrated Model – Glacier dynamics), were used. WASA is a semi-distributed glaciohydrological model that simulates snow and glacier cover as well as the catchment hydrology at a daily time step (Güntner and Bronstert, 2004). The spatial structure is based on catchments, subcatchments and 200 m elevation zones. The spatial variability of snow within an elevation zone is represented by a snow depletion curve (Liston, 2004). Snow is further redistributed from higher to lower elevation zones if simulated snow outside a glacier accumulates above a given snow water equivalent threshold. Glacier area and surface elevation changes are simulated using the Δh-approach by Huss et al. (2010), and updated annually. Glaciers are considered individually and discretized into 50 m elevation bands. Based on the simulated mass balance of the glacier, thickness changes in each elevation band are calculated using predefined functions derived from observed glacier thickness changes of the Ak-Shirak massif, located at the western border of the Aksu Basin, in the period 1977–1999 (Surazakov and Aizen, 2006). The glacier area is reduced if the thickness change in an elevation band is higher than the remaining ice thickness. Snow and glacier melt are calculated using a temperature-index approach (Hock, 2003). A detailed model description can be found in Duethmann et al. (2016).

SWIM-G is the glaciohydrological version of the semi-distributed, ecohydrological model SWIM (Soil and Water Integrated model; Krysanova et al., 1998). It was used to simulate both individual glaciers

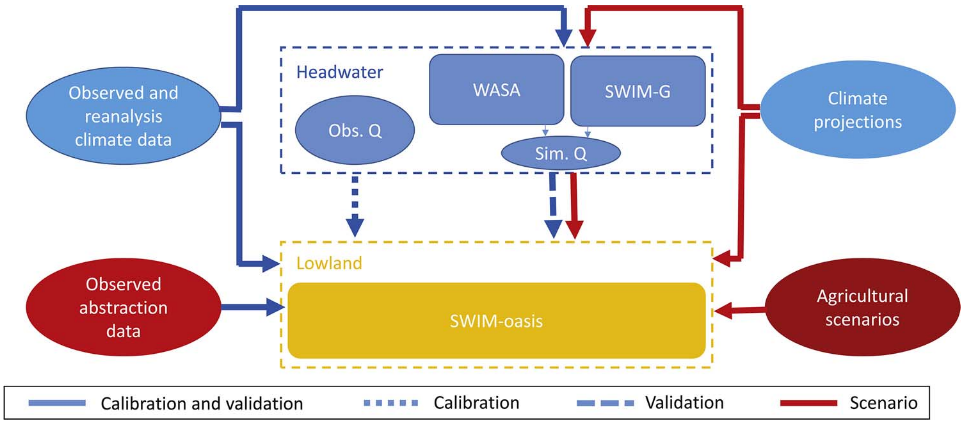

Fig. 3. Flowchart of the models and the major input data.

and the catchment hydrology of the five headwaters in a tightly integrated approach (Wortmann, 2017). It relies on computational units that disaggregate complex terrain into parts of similar elevation, aspect and hydrological subbasin (glaciological response units), as opposed to gridded (fully distributed) or empirical approaches (Immerzeel et al., 2011; Huss et al., 2010). The units are conceptually similar and computationally equal to the hydrological response units (HRUs). The mass balance is evaluated considering snow accumulation based on threshold temperature as well as avalanching, and an enhanced Degree-Day melting approach. The latter includes aspect and terrain shading, debris melt-out and sublimation. Like most hydrological processes, the glacier processes are computed daily for each unit and ice is routed laterally between them according to an adapted Glen's Flow Law approach (Marshall et al., 2011).

The SWIM-G and WASA models were successfully calibrated and validated for the five headwater gauges at the daily time step against river discharge, glacier area hypsometery and mass balance (SWIM-G) and against river discharge and glacier mass balance (WASA). Since glacier mass balance data during the simulation period were only available in the Aksu basin, we derived assumptions based on IceSAT data, which are available for a more recent period, for the Hotan and Yarkand basins. Both models successfully reproduced daily river discharge in all five headwaters (daily Nash and Sutcliffe efficiency (NSE) between 0.60–0.85, absolute bias less than 15% in the calibration period, and NSE between 0.70–0.80, absolute bias less than 15% in the validation period). The details of the calibration/validation procedure and results are reported in Duethmann et al. (2016) and Wortmann (2017).

Results of the impact assessment for the headwaters show an initial increase in river discharge in the first scenario period (2011–2040) by 20–30% at the ensemble median, similar to the changes that have already been observed. Subsequent changes are strongly scenario-dependent and show increasing discharge in the Hotan and Yarkand in all periods (30–50% at the ensemble median). Glacier area loss over the 21 st century is limited to ca. 20% under the RCP2.6 scenario but as high as 75% in the higher end scenarios. While glaciers are generally on the decline causing an eventual decrease in melt water by the end of the century, precipitation is also projected to increase in the region. The WASA and SWIM-G models indicated that this increase is able to partially counterbalance melt water losses in downstream discharge. The full results for the headwaters are published in Duethmann et al. (2016) and Wortmann (2017).

3.2. The SWIM-oasis model

The SWIM-oasis model is a version of SWIM adapted to the arid oasis environment of the Taklamakan Desert with a simple irrigation module and a river transmission loss module (Huang et al., 2015).

In the irrigation module, the HRUs are discretized by subbasins, land use, soil types and the boundaries of the administrative units (i.e. counties or the Agricultural Divisions). The HRUs belonging to a certain administrative unit receive the abstracted water from a specific river reach. The actual daily abstraction for each administrative unit is estimated to be the minimum value of either the calculated daily water demand and the discharge of the linked river reach.

The abstracted water is separated into two parts based on the CIE: irrigation water which is applied to irrigated fields and the conveyance loss in the transportation systems between the river and field. The irrigation water is directly applied to the agricultural HRUs as precipitation while the conveyance loss is applied to other HRUs within the same administrative unit to consider water use by natural vegetation. Both the irrigation water and conveyance loss are included in the hydrological cycle, and are not lost from the water balance.

There are four control volumes in the SWIM-oasis model: the soil surface, the root zone of soil, the shallow aquifer and the deep aquifer. The water balance for the soil surface and soil column includes precipitation, surface runoff, evapotranspiration, subsurface runoff and percolation. The water balance for the shallow aquifer includes groundwater recharge, capillary rise to the soil profile, percolation to the deep aquifer and return flow to the river.

The module representing crops and natural vegetation applies a simplified EPIC approach (Williams et al., 1984) in the SWIM-oasis for simulating arable crops and other vegetation types. Vegetation in the model affects the hydrological cycle through the land cover-specific retention coefficient, which influences surface runoff, and through the leaf area index (LAI), which influences transpiration.

There are two approaches applied for the estimation of river transmission losses. In the wet period (summer), the SWIM-oasis model estimates the infiltration losses as a product of hydraulic conductivity, travel time, wetted perimeter and length of river channel, and the evaporation losses as the product of potential evaporation, river channel length and surface channel width. Since the river cross section characteristics may change significantly during the dry period (winter), a more empirical approach was used for this period. The mean river channel width is estimated from the inflow to the considered subbasin after Leopold (1994). The river transmission losses are then derived from the linear regression equation used by Lane (1990).

The SWIM-oasis model was compared with the WEAP model (Water Evaluation And Planning) (SEI, 2005) for simulating the downstream discharge of the Aksu River (Huang et al., 2015). The WEAP model only considers water withdrawal from rivers without simulation of further hydrological processes, while the SWIM-oasis model includes mathematical description of the full hydrological cycle, and can simulate river transmission losses, recharge of the shallow aquifer and groundwater return flow. The SWIM-oasis results show that the summer peaks are better comparable with observations than the WEAP results due to

Table 1
List of available time series data used in the study.

	Basin	Gauge/Data	Variable	Source	Resolution	Time period
Hydrological data	Aksu	Xiehela	Discharge	Hydrological year book	Daily	1964–1987
			Discharge/water amount	Wang (2006)	Monthly	1957–2004
		Shaliguilanke	Discharge	Hydrological year book	Daily	1964–1987
			Discharge/water amount	Wang (2006)	Monthly	1957–2004
		Xidaqiao	Discharge/water amount	Wang (2006)	Monthly	1957–2004
	Hotan	Wuluwati	Discharge	Hydrological year book	Daily	1977–1988[a], 2007–2010
		Tongguziluoke	Discharge	Hydrological year book	Daily	1983–1988[a], 2007–2010
		Wuluwati + Tongguziluoke	Water amount	Huang and Shen (2010)	Annual	1971–2003
		Xiaota	Discharge	Hydrological year book	Daily	1964–1988
			Water amount	Huang and Shen (2010)	Annual	1971–2003
	Yarkant	Kaqun	Discharge	Hydrological year book	Daily	1964–1988, 2001–2003, 2007–2010
		Heiniyazi	Discharge	Hydrological year book	Monthly	1964–2005
	Tarim	Alar	Discharge	Hydrological year book	Daily	1965–1988, 2001–2003, 2007–2010
			Discharge/water amount	Wang (2006)	Monthly	1957–2003
Climate data	The whole catchment	WATCH	Temperature (max, min, mean), relative humidity, rediation	Weedon et al. (2011)	Daily	1960–2001
		APHRODITE	Precipitation	Yatagai et al. (2012)	Daily	1950–2007
	Aksu (headwater)	Station data	Precipitation, Temperature	Kyrgyz Hydrometeorological Service	Daily	1957–2004
Abstraction data	Aksu		Annual abstraction[b]	Wang (2006)	Annual	1984–2005
			Monthly abstraction	Wang (2006)	monthly	1998, 2005
	Hotan		Annual abstraction	Huang and Shen (2010)	Annual	1971–2003
			Monthly abstraction	Xinjiang Tarim River Basin Management Bureau	Monthly	2003
	Yarkant		Annual abstraction	Xinjiang Tarim River Basin Management Bureau	Annual	1982–1999
			Monthly abstraction	Xinjiang Tarim River Basin Management Bureau	Monthly	2000–2002

[a] Data is also avaiable in 1970s, but with ca. 50% missing values.
[b] Estimated from discharges in the main diversion channels.

inclusion of river transmission losses. The winter low flows simulated by SWIM are higher than those simulated by WEAP due to groundwater contribution to streamflow, resulting in a better representation of the observed flows in winter. The results indicated that the SWIM-oasis model is capable to simulate irrigation water movement and reproduce satisfactorily the monthly discharge of the Aksu River. More details about the SWIM-oasis model and its results can be found in Huang et al. (2015).

3.3. Calculation of water demand for agricultural scenarios

In our study, the annual and monthly irrigation demands were estimated using the local irrigation instructions before application of the SWIM-oasis model. This was preferred over using standard approaches from other models, e.g. by filling soil layers up to field capacity, as in the SWAT model (Soil and Water Assessment Tool, Neitsch et al., 2005), or by estimation of difference between the crop-specific potential evapotranspiration and effective precipitation as in the WaterGAP3 model (Aus der Beek et al., 2011). This was done for the following reasons. Firstly, the surface irrigation technology (surface flooding) is prevailing in the study area. Secondly, there is a need to irrigate in winter and spring before the growing season to achieve salt leaching and soil moisture maintenance. Thirdly, the ultimate objective of the study is to simulate discharge at Alar, and the standard approaches cannot estimate the actual water use in our basins correctly. Also Dechmi et al. (2012) found for their study area in Spain that it was not appropriate to simulate streamflow using the standard approach in the SWAT model, and they defined the amount of irrigation water using data on irrigation operations instead.

The estimation based on the irrigation instructions needs data on the irrigation schedule, irrigation quotas, the irrigation area, and the CIE. As there is no detailed information about the daily irrigation practices, we assumed that the irrigation quota is evenly distributed in each irrigation period. Given the irrigation area (*Area*: ha) and the daily irrigation quota (*Quota*: m^3/ha) for each crop, the daily irrigation demand of each administrative unit (*ID*: m^3) can be calculated using Eq. (1):

$$ID_j = \sum_{i=1}^{13} (Area_{i,j} * Quota_{i,j}) \tag{1}$$

where j indicates the administrative unit, and i is the crop type. Then the monthly (MID_j) and annual (AID_j) irrigation demands for each river basin can be summed by the daily values. The monthly share is obtained by the ratio of MID_j to AID_j. Finally, the total annual water demand (TAD_j) is calculated using Eq. (2):

$$TAD_j = AID_j / c_j, \tag{2}$$

where c is the CIE of administrative unit j.

This calculation method has proven to be reliable to estimate the annual water use and monthly variations in our previous study for the Aksu basin (Huang et al., 2015).

3.4. Evaluation of uncertainty from different sources

In this study, we applied the ANOVA method to partition simulated variances into different contributing sources (Bosshard et al., 2013; Vetter et al., 2015). We investigated the following sources: climate models (CM), agricultural scenarios (AS) and hydrological models

(HM). The ANOVA method not only provides information about the impact of the uncertainty from these three major sources on river discharge, but also their interaction terms (CM*AS, AS*HM, CM*HM and CM*AS*HM). To avoid the bias caused by different sample sizes of the sources, the ANOVA was implemented for a number of subsamples, each of which includes two agricultural scenarios, two climate models and two hydrological simulations. The obtained estimates were then averaged. For more explanation of the method and equations, please refer to Vetter et al. (2015).

3.5. Data for hydrological model setup, calibration and validation

In order to keep consistence with the headwater modeling, the SWIM-oasis model was set up using the SRTM digital elevation model (SRTMv4 90m, Jarvis et al., 2007) to delineate the watersheds. Soil data were derived from the Harmonized World Soils Database (FAO et al., 2012). Land cover information was taken from the Chinese land use map for year 2000.

There is almost no observed climate data available in the mountainous areas, especially in the Hotan and Yarkand river basins. Therefore, we had to use reanalysis data with coarse resolutions for the entire Upper Tarim Basin. Temperature (mean, minimum and maximum), air humidity and solar radiation data available from the WATCH project at 0.5 arc degree for the period 1957–2001 (WFD-ERA40) (Weedon et al., 2011) was used (Table 1). The precipitation data was taken from APHRODITE (Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation, Version: V1101) (Yatagai et al., 2012), which is considered more reliable than the WATCH precipitation data because it used data from more observation stations as a basis.

The discharge data was obtained from different sources, in different temporal resolutions and for different periods (see Table 1). For all headwater gauges, the daily discharge was available from the hydrological yearbook, but only until 1987 or 1988, and for several recent years (e.g. 2007–2010). For the gauge stations in the Aksu River and the Alar station, the long-term monthly discharge (1957–2003/2004) was available from Wang (2006). For the outlet station Xiaota at the Hotan River, daily discharge from 1964 to 1988 was available, while there was only monthly discharge available for Heiniyazi at the Yarkand River.

The observed annual water abstraction data was available for different time slices in each river basin. In the Aksu River basin, the annual abstraction data was estimated by the water amount in the main cannels from 1984 to 2005 (Wang, 2006). The long-term mean annual abstraction data (1971–2003) for the Hotan River basin was taken from Huang and Shen (2010), and the annual abstraction data from 1982 to 1999 for the Yarkand River basin was obtained from Xinjiang Tarim River Basin Management Bureau. The monthly abstraction data, which was used to calculate the shares of monthly water demand, and the CIE were available only for 1998 for the Aksu (Wang, 2006), for 2000–2003 for the Yarkand, and for 2002 for the Hotan, and were extrapolated for other years.

As it is shown above, the data availability in our study area is inconsistent in time. There were only a few overlaps in periods between the availability of the observed discharge data and water abstraction data, so we had only short periods to calibrate and validate the hydrological models (see Section 4.1). The data problems will be discussed in more detail in Section 5.

3.6. Climate scenarios

There were four climate projections of regional climate models (RCMs) available for this study. They are: three CCLM (Cosmo-Climate Local Model) (Rockel et al., 2008) projections for RCPs (Representative Concentration Pathways) 2.6, 4.5 and 8.5 driven by the GCM (General Circulation Model) MPI-ESM-LR, and one A1B scenario generated by the RCM REMO (Jacob, 2001) driven by the GCM ECHAM5 (Mannig et al., 2013). The spatial resolution of the CCLM and REMO outputs are 0.44° and 0.11°, respectively.

The set of RCM projections was extended by including 24 GCM projections (CNRM-CM5, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM and MRI-CGCM3) representing 3 RCP scenarios (RCP 2.6, 4.5 and 8.5).This ensemble enabled us to analyze uncertainties related to climate models. The spatial resolution of the GCM outputs are between 1.12° and 3.75°.

The historical simulations of all climate models cover a period from 1960/1961 to 2000, and the climate projections start from 2001/2006 and end in 2099. The GCM/RCM outputs were downscaled/upscaled to a resolution of 0.5° and bias corrected to the WATCH and APHRODITE data for the period 1960–2000 using the quantile mapping method (Gudmundsson et al., 2012). In addition, we use a trend adaptation approach to preserve the trend similar to Hempel et al. (2013). The reference period is 1971–2000 and three scenario periods were selected for the near (2011–2040), medium (2041–2070) and far (2071–2099) future. Appendix B shows the list of projections and their climate change signals in each scenario period.

3.7. Agricultural scenarios

In 1998, when the government improvement plan (GXUAR and MWRC, 2002) was proposed, the water resource conditions in this year were considered as an important reference. As a result, more management data was available for this year, especially for the Aksu basin. In addition, Liu et al. (2010) suggested to consider the agricultural area in 1998 as an objective for the future control of cropland. Therefore, we developed a reference scenario based on agricultural and management data in 1998, and the water flows simulated using this scenario were considered as corresponding to the governmental objective. Based on this reference scenario, a number of combinations of agricultural scenarios were developed (see Table 2).

In this study, we used the irrigation instructions for the Awati County to estimate the irrigation demands for the whole study area for the following reasons. First, the irrigation instructions were only available for the counties in the Aksu basin (Wang, 2006) in this study, and the irrigation quota and schedule are similar across counties in Aksu. Second, the Awati County is the closest county to the Hotan and Yarkand river basins. This allows to assume that the differences among them are not significant.

There are five major scenario conditions related to agriculture area, crop distribution, CIE, drip irrigation ratio and river transmission losses, and each of them has 2–3 options (or sub-scenarios, as in Table 2). The latter four scenario conditions are related to water saving measures.

The first major scenario condition is related to agricultural area, and the sub-scenario A_0 means no changes in agricultural area, referring to the agricultural area as in 1998 (reference). Sub-scenario A_1 assumes a significant increase in cropland (by 100% in the Aksu and Yarkand, and 40% in the Hotan) corresponding to the actual changes between 1998 and 2010 (Fig. 2), i.e. to arable land area in 2010. Since the irrigated area has been still growing after 2010, the third sub-scenario A_2 considers a further increase by 150% in the Yarkand and 60% in the Hotan. No further changes were considered in the Aksu because the headwater discharge tends to decrease in the far future under climate scenarios (Duethmann et al., 2016).

The second scenario condition is related to crop distribution and includes two sub-scenarios: C_0 assumes no changes in crop distribution (as in 1998, reference), and C_1 corresponding to crop distribution as in 2010. No additional sub-scenarios were included, as the influence of crop distribution is not significant, as was shown in our previous study (Huang et al., 2015).

The third scenario condition considers an improvement of leakage-proofing of canals between river and fields. The current CIE is between

Table 2
Agricultural and water management scenarios for the Upper Tarim basin.

Scenario conditions	sub-scenario	Aksu							Hotan							Yarkant						
A: Change in agricultural area (%)	A0 (reference)	0							0							0						
	A1	100							40							100						
	A2	100							60							150						
C: Change in crop distribution (%)		WW[a]	Ma.	Rice	Cot.	Fru.	For.	Oth.	WW	Ma.	Rice	Cot.	Fru.	For.	Oth.	WW	Ma.	Rice	Cot.	Fru.	For.	Oth.
	C0 (reference)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C1	−7	−1	−5.5	−2	16	3	−3.5	−8	−7	−1	−14	15	7	8	−7	−4	−1	−16	14	0	14
E: Conventional irrigation efficiency	E0 (reference)	0.49							0.395							0.373						
	E1	0.53							0.53							0.53						
	E2	0.57							0.57							0.57						
D: Drip irrigation ratio (%)	D0 (reference)	0							0							0						
	D1	25							25							25						
	D2	50							50							50						
R: Change in river transmission losses (%)	R0 (reference)	0							0							0						
	R1	0							−15							−15						
	R2	0							−30							−30						

[a] WW: winter wheat; Ma.: Maize; Cot.: Cotton; Fru.: fruit; For.: forest; Oth.: Others.

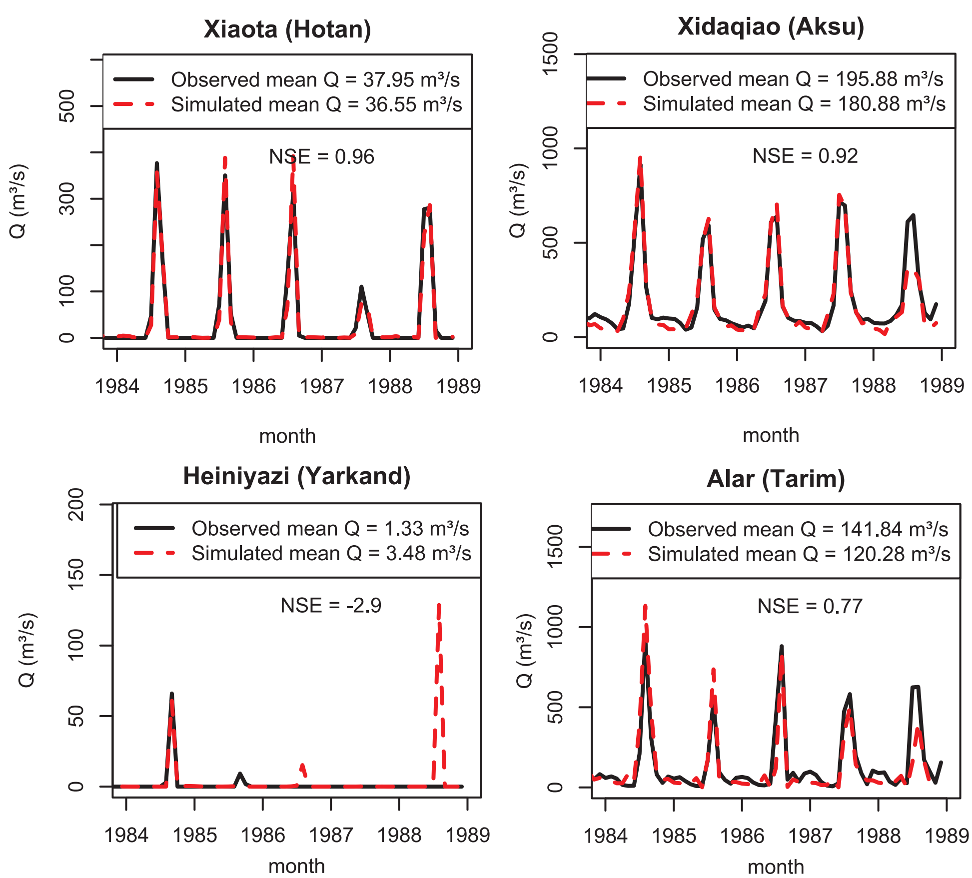

Fig. 4. Comparison of observed and simulated monthly discharges by SWIM-oasis at Alar and the gauges in the lowland areas of the Aksu, Hotan and Yarkand rivers in the calibration period 1984–1988.

0.37 and 0.49 in the three basins, meaning that only 37–49% percent of extracted water reaches the root zones. According to the Ministry of Agriculture of the People's Republic of China, the aim is to increase the CIE in Xinjiang province to 0.53 by the end of 2015 and to 0.57 in 2020. Hence, the sub-scenarios include: E_0 with CIE as in 1998 (reference); E_1 with CIE equal to 0.53, and E_2 with CIE equal to 0.57.

The fourth scenario condition accounts for the ratio of the drip irrigation area to the whole irrigation area. As the surface irrigation was prevailing in 1998 and previous decades, we designed three sub-scenarios: D_0 with no drip irrigation as in 1998 (reference), D_1 assuming the drip irrigated area of 25% of total, and D_2 of 50% of total.

The last scenario condition considers the potential reduction of river transmission losses in the Hotan and Yarkand rivers by restoration of the riverbeds. The reference sub-scenario R_0 assumes that there are no changes in the transmission loss coefficient. According to Liu et al. (2010), the restoration of the middle Tarim riverbed saved about 30% of water amount from Alar. So, we assumed the potential reduction of river transmission losses by 15% and 30% for the Hotan and Yarkand rivers in scenarios R_1 and R_2, respectively. For the Aksu River, no reduction of river transmission losses is considered as the river is short

and well regulated.

In total, there are a maximum of 162 combinations of the agricultural and water management scenarios. The combination of all first sub-scenarios, named as $A_0C_0E_0D_0R_0$, denotes the reference scenario. In addition, we selected 30 combinations to study the impacts of individual and combined measures (Appendix C). For example, scenario $A_1C_1E_2D_2R_2$ means an increase in irrigated area by 100% in the Aksu and Yarkand basins and 40% in the Hotan basin; crop distribution as in 2010; CIE of 0.57; application of the drip irrigation method at about 50% of area; and reduction in river transmission losses of about 30% in the Hotan and Yarkand rivers.

4. Results

4.1. Calibration and validation

Due to the different temporal availability of climate, discharge and water abstraction data (Table 1), the SWIM-oasis model was calibrated only for the period from 1984 to 1988 using the observed headwater discharges and abstraction information as input. The reason for using the observed headwater discharge is to avoid errors from the simulated headwater discharge and calibrate the river transmission losses correctly. However, due to a lack of observed discharge data after 1989, SWIM-oasis could only be validated for the period 1989–2000 at the Alar station using the simulated headwater discharge by the SWIM-G or WASA models as input.

Fig. 4 shows the observed and simulated monthly discharges at the gauges Xiaota (Hotan), Xidaqiao (Aksu), Heiniyazi (Yarkand) and Alar (Tarim) during the calibration period. In general, the simulation results for the Hotan River are in good agreement with the observed discharge (NSE is 0.96). The seasonal dynamics of the Aksu River discharge is also well simulated with NSE of 0.92, but the total amount is slightly underestimated. The discharge of the Yarkand River is overestimated for the year 1988. For this river, with very low mean observed discharge of $1.33\,m^3/s$, discharge is very sensitive to any human interferences. A slight underestimation of the abstraction can increase discharge at the river outlet significantly. Overall, the simulated discharge at Alar is acceptable with NSE of 0.77 and an underestimation of about 15%, which is mainly due to the underestimation of the Aksu River discharge.

Fig. 5 shows the validation results of the monthly discharge at Alar for the period 1989–2000 using the simulated headwater discharges from WASA and SWIM-G models separately. Since the abstraction data and the SWIM-oasis model are the same, the differences between the validation runs are associated with the simulated headwater discharges by the two models. In general, both combinations of the hydrological models could generate average monthly discharge at Alar satisfactory (see graphs on the right), with NSE larger than 0.8 and bias within the range of ± 10%. However, both combinations of models slightly underestimate discharge in June and July, probably due to the share of monthly water demand which was derived from the data from some certain years (see Section 3.5). A reasonable simulation of average monthly discharge is important for this study, as the mean annual and monthly discharges over the reference and scenario periods were used for climate impact analysis.

4.2. Potential change in river discharges under climate change

To assess the impacts of pure climate change, the SWIM-oasis model was run with the simulated headwater discharges from the SWIM-G and WASA models under the same climate projections and the agricultural reference scenario $A_0C_0E_0D_0R_0$. The simulated results for the reference period were considered as the reference discharge or the government objective. Changes are calculated between this reference discharge and the simulated discharge in the future.

The upper three graphs in Fig. 6 show the relative changes in annual mean discharge at Alar for the three scenario periods under the A1B scenario from REMO and three RCP scenarios from CCLM. All results show that there would be an increase in discharge at Alar throughout the century except for the WASA + SWIM-oasis results under the A1B scenario in the far future period (2071–2099). The increase in discharge is mainly due to increase in melting water under a warmer climate and increase in precipitation, especially in the Hotan and Yarkand headwaters (see Appendix B). However, the increase in the far future is less prominent than in the near and medium future probably due to glaciers shrinkage in the headwater basins. In general, the combination of WASA and SWIM-oasis generates greater increase than the SWIM-G and SWIM-oasis models in the near future but lower increase or a decrease in the far future. It shows that the differences between the two glaciohydrological models lead to discrepancies in the projection of water resources for this semi-arid region, especially in the far future.

In addition to the total annual relative changes, we also compared the seasonal distribution of the total annual changes (Fig. 7). Simulated by two combinations of hydrological models under two scenarios (RCP2.6 and RCP8.5), the increase in discharge is dominant in four

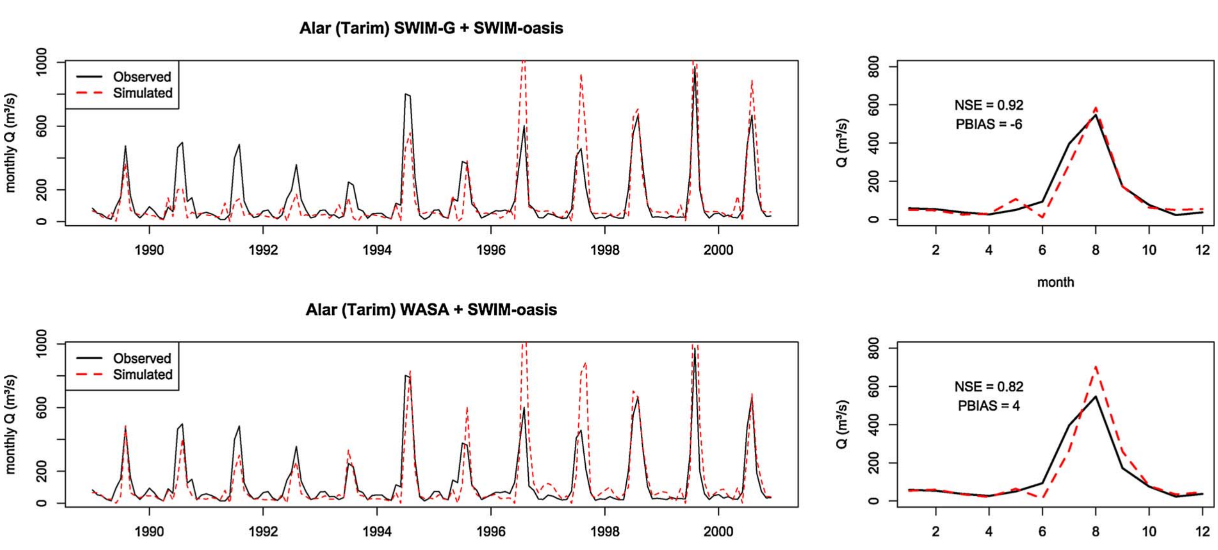

Fig. 5. The monthly observed and simulated discharges (left) at Alar for the validation period 1989–2000 using the simulated headwater discharge from the SWIM-G model (upper) and WASA model (lower) as input. The average monthly discharges were shown on the right. The NSE was calculated for the average monthly discharges.

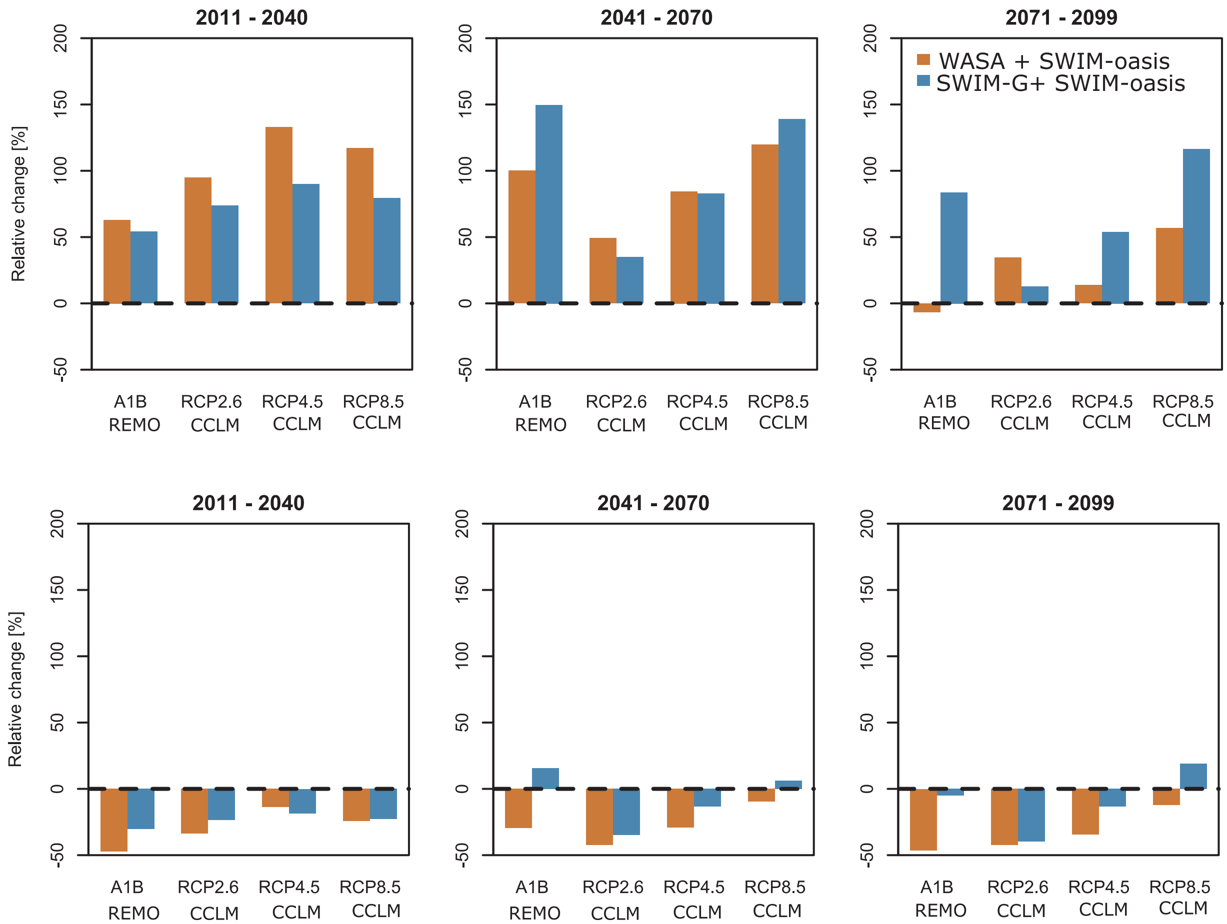

Fig. 6. Relative changes in the long-term mean annual discharge at Alar in three future periods under climate change scenarios simulated by two RCMs compared to the reference period. The agricultural area is assumed to stay at the level of 1998 (upper three figures) and 2010 (lower three figures), and no water saving measures are applied.

months from June to September. There is hardly any increase in March, April and November. The projected increase in discharge during summer (the high flow period) would be especially beneficial for the main Tarim River, because the river water can only reach the downstream Tarim when the discharge at Alar exceeds 400 m^3/s for more than 20 days (Chen et al., 2009).

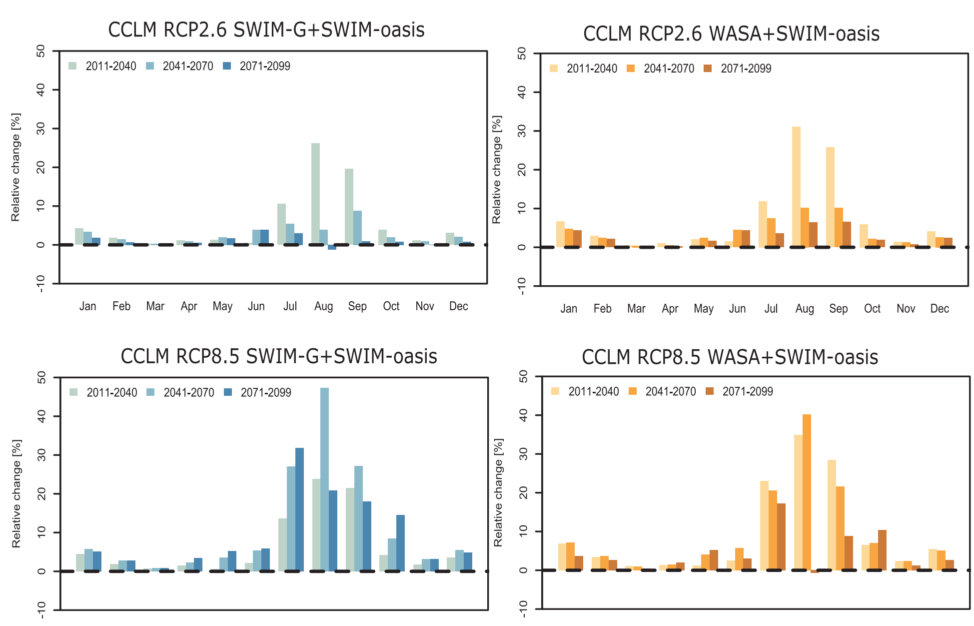

Fig. 7. Relative changes (%) in the long-term average monthly discharge at Alar in three periods under climate change projections from two RCMs compared to the reference period. The agricultural area is assumed to stay at the level of 1998, and no water saving measures are applied.

4.3. Potential changes in river discharges under both agricultural and climate scenarios

The results in Section 4.2 show that the objectives of the governmental plan could be achieved under the warming climate if the agricultural area would return to the extent of 1998, even without any water saving measures. However, the historical trend of the agricultural area in this region shows that it is almost impossible or very difficult to reduce the agricultural area to the level as in 1998 (Fig. 2). The local people extended agricultural area whenever they had more water available in the rivers. Hence, it is interesting to know what happens if the agricultural area would stay at the level of 2010 (scenario $A_1C_0E_0D_0R_0$).

The lower three graphs in Fig. 6 show the relative changes in the annual mean discharge at Alar under four RCM climate projections and the agricultural scenario $A_1C_0E_0D_0R_0$. The agricultural area as in 2010 leads to a significant reduction of discharge (up to 50%) under all climate scenarios except the REMO A1B scenario in the medium future and the CCLM RCP8.5 scenario in the far future. This indicates that the increase in the headwater discharges cannot compensate the increase in the irrigation water demand caused by an extended cropland, and the objective of the governmental plan can be hardly achieved, if the agricultural area remains as in 2010 without any saving water measures.

Fig. 8 shows a comparison of the effects of different combinations of agricultural scenarios under all four RCM projections (shown as vertical bars). Comparing the single moderate water saving measures, we can see that change in crop distribution (scenario $A_1C_1E_0D_0R_0$) leads to minor changes of only 2–5% in river discharge compared to scenario $A_1C_0E_0D_0R_0$. Improvement of the CIE (scenario $A_1C_0E_1D_0R_0$) substantially reduces the irrigation water demand, and leads to a positive change, saving about 15–50% water in the near future and 6–30% water in the far future. The effect of this measure is less significant in the last period probably due to lower water availability in rivers in this period (see Fig. 6). The other two moderate measures, an increase of drip irrigation area (scenario $A_1C_0E_0D_1R_0$) and a reduction of river transmission losses (scenario $A_1C_0E_0D_0R_1$), lead to savings of about 2–15% and 4–5% of water in the near future and 2–3% and 4–7% of water in the far future, correspondingly. When all moderate measures (scenario $A_1C_1E_1D_1R_1$) are combined, the effect is strong, and mostly positive changes in river discharge are projected. If all strong measures (e.g. scenario $A_1C_1E_2D_2R_2$) were applied in combination, the governmental objective would always be achieved no matter which RCM climate scenario would be realized. However, if the agricultural area increases further (scenarios $A_2C_1E_1D_1R_1$ and $A_2C_1E_2D_2R_2$), there is still a risk of water reduction in the Tarim in the far future, especially if the moderate measures are applied.

Finally, we compared the results driven by three CCLM projections with the ones driven by 24 projections from GCMs, for the three RCPs. Fig. 9 shows selected results for four agricultural scenarios (reference scenario $A_0C_0E_0D_0R_0$, scenario $A_1C_0E_0D_0R_0$, scenario $A_1C_1E_1D_1R_2$ and scenario $A_2C_1E_2D_2R_2$). In general, the results driven by the CCLM projections are always within 25% to 75% percentiles of the projections driven by the GCMs. The results from the combination of WASA and SWIM-oasis models usually have larger ranges (i.e. higher uncertainty) than the ones from the SWIM-G + SWIM-oasis models, and they often project more negative changes in river discharge in the medium and far future. There is also larger uncertainty in the projections under the higher RCP scenarios.

Compared to the results driven by the CCLM outputs, the ensemble results under all 24 GCM projections show a high risk of decreases in river discharge. For example, positive changes were projected under the CCLM RCP8.5 scenario and the agricultural scenarios $A_1C_1E_1D_1R_1$ and $A_2C_1E_2D_2R_2$, but about half of the ensemble results driven by the GCM RCP8.5 scenarios show negative changes simulated by the WASA and SWIM-oasis models. This is likely due to the lower temperature increase projected by CCLM as compared to the mean of the selected GCMs. In addition, it indicates that even the strong water saving measures suggested in this study cannot ensure water resources availability in the Tarim River at the end of this century due to uncertainty in future climate. It should also be noticed that the uncertainty of projections under the high RCP scenarios is much larger than that under the lower ones. Hence, it would be more difficult to make management decisions based on such large uncertainties from the high RCP scenarios.

4.4. Quantifying different sources contributing to projection uncertainty

As shown in Section 4.3, the uncertainty in projected results caused by climate models (including both RCM and GCMs), hydrological models and agricultural scenarios is substantial. Fig. 10 illustrates the

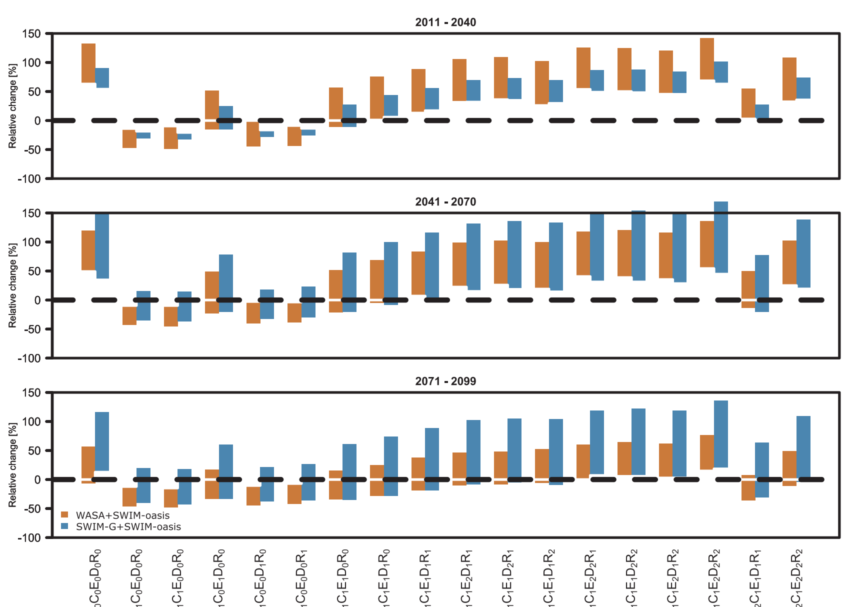

Fig. 8. Long-term mean annual relative changes in discharge (%) at the gauge Alar under different water management scenarios. Each of the floating bars includes the results driven by four RCM projections.

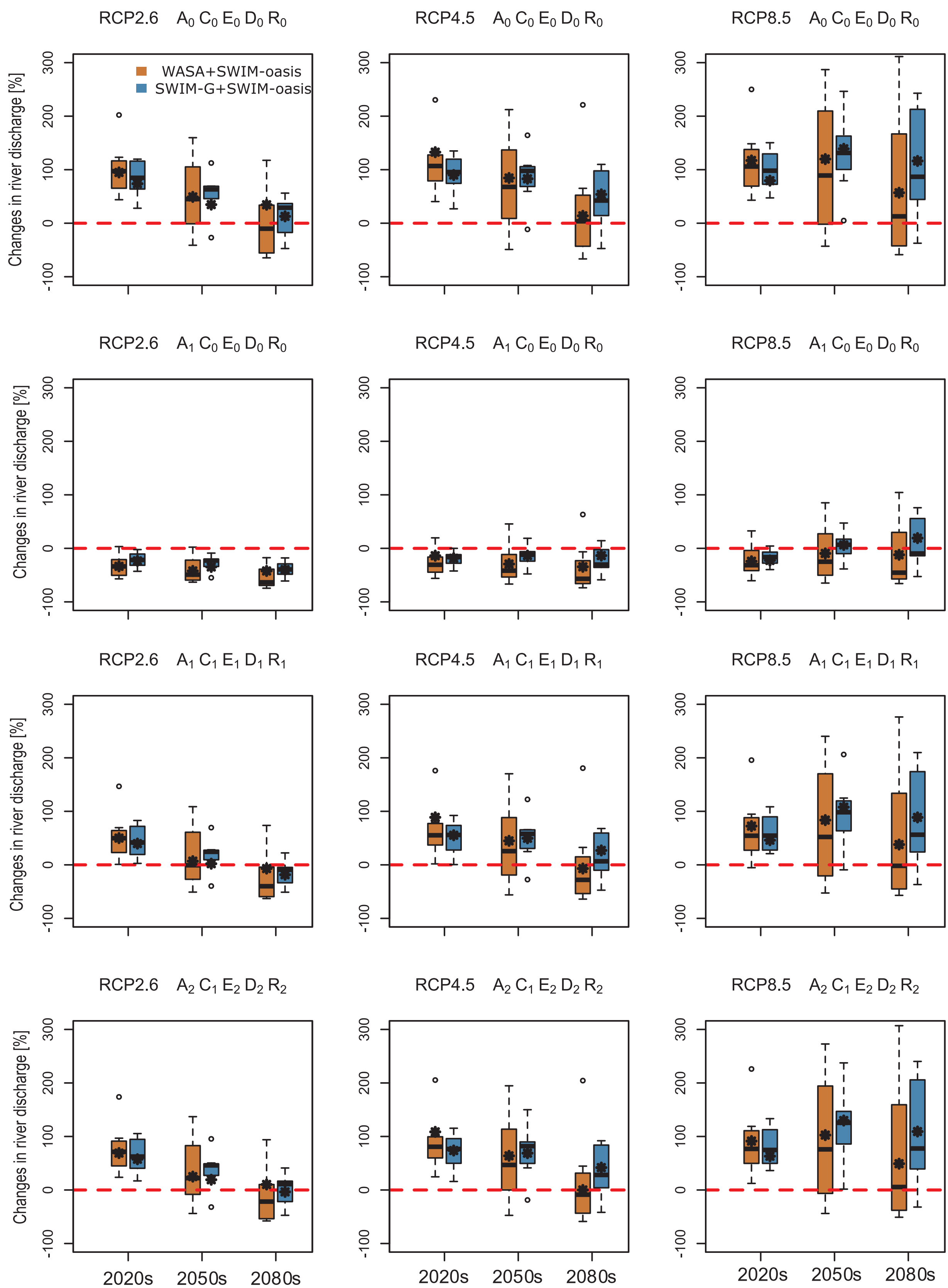

Fig. 9. The long-term mean annual relative changes in discharge (%) at the gauge Alar in three scenario periods for three RCP scenarios (each column) and four selected agricultural scenarios (each row). The boxplots include model outputs driven by the GCM projections, and the stars indicate the outputs driven by the CCLM projections.

contribution of different sources to the overall uncertainty of the projected changes in three scenario periods for each RCP scenario.

In general, the relative uncertainty caused by climate models increases with RCP forcing. In the near future, the agricultural scenarios explain more than 40% of the total uncertainty, and the climate models contribute to about 30%. The hydrological models contribute only

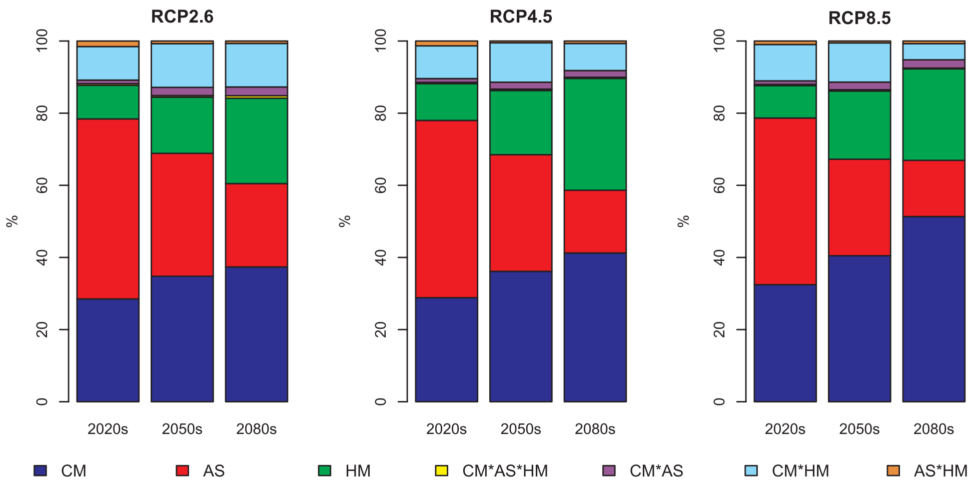

Fig. 10. Composition of variation of river discharge at the Alar station including different sources and interaction terms for three scenario periods. Here CM: climate models; AS: agricultural scenarios; HS: hydrological simulations.

about 10% indicating that the hydrological simulations for the headwaters are relatively robust. In the medium future, the uncertainty caused by the agricultural scenarios is reduced by 15–20% while the uncertainties caused by the climate and hydrological models increase by about 7–10%. In the far future, the agricultural scenarios become even less important, and the climate and hydrological models play major roles in the uncertainty of the projections. Note that the absolute uncertainty caused by the agricultural scenarios remains the same in all three periods and RCP scenarios, and the total absolute uncertainty increases in the medium and far future and in higher RCPs due to the increasing uncertainty related to the climate models and hydrological models.

5. Discussion

A novelty of this study is the application of multiple climate projections and agricultural scenarios and two combinations of hydrological models in the climate adaptation assessment. The agricultural scenarios include not only changes in agricultural areas but also the water saving measures proposed by the government plan and previous studies. These scenarios are based on the current trends and assumptions, but they can be modified under the rapid economic and technological developments of the region.

However, we should notice that this study only assessed the impacts on river discharge, and further efforts are required to assess the influence on the oasis environment and social-economic development. For example, a reduction of agricultural area to the level of 1998 is the most effective measure to ensure the discharge quota at Alar, but it may harm the local farmers' interests. This is also related to the change of crop distributions, as both crop water demand and the economic interests should be considered. The improvement of CIE, use of drip irrigation and restoration of river bed could reduce agricultural water use and river transmission losses, but they could also reduce groundwater recharge and the ecological water use in the oases areas and riparian zones (Zhong et al., 2009). As a result, the whole oasis ecosystem could be negatively affected. In addition, drip irrigation as well as other deficit irrigation methods using the highly mineralized river water could lead to degradation of soil quality. Such water saving technologies must be combined with flood irrigation after the growing season to reduce salt accumulation in the soil profile (Chen et al., 2010).

At present, the Aksu River is the most important water source for the Tarim River, but its discharge is likely to decrease under a warming climate mainly due to the retreat of glaciers (Duethmann et al., 2016). An interesting finding of this study is that the increase in discharge at Alar is mainly due to the increase in the headwater discharges of the Hotan and Yarkand rivers in the future (described in Section 3.1 and Wortmann, 2017). Despite the rapid glacier and snow melting under higher temperatures, the increase in precipitation in the mountainous regions is prominent under higher RCP scenarios (see Appendix B). If the water demand can be controlled properly and the river transmission losses are reduced, the Hotan and Yarkand rivers can become more important water sources to the Tarim River in the future.

Another important finding of this study is that there is no high risk to have less annual water in the Tarim River under high RCP scenarios. These results are consistent with the pure climate impact study by Liu et al. (2013) under the A1B, A2 and B1 scenarios, especially at the end of this century. However, the stakeholders should not be too optimistic as the low RCP scenarios may be more likely to realize after the climate change conference in Paris. Under the RCP2.6 scenario, the discharge at Alar is likely to decrease at the end of this century under more than half of the projections by both combinations of hydrological models.

The RCM scenarios are usually considered to be more precise and reliable than the GCM scenarios for the regional climate impact studies (Elguindi et al., 2011). However, the high-resolution RCM scenarios (REMO) in this study could not provide much better spatial information than the GCM scenarios, because they were upscaled and bias-corrected using the reanalysis data (0.5°). In order to make use of the RCM scenarios in the future, reliable observed climate data would be helpful to correct the RCM data at a finer resolution. Moreover, the resolution of the applied RCMs is still very coarse for such a complex high-mountain region and even finer resolution of the RCM projects are preferred in the future.

Due to lack of the observed climate data in our study, the simulation of water generation is afflicted with high uncertainties. The large differences in the projections between the two glaciohydrological models are attributed not only to their different methods of calculating snow and glacier processes but also to the equifinality problem caused by the uncertainty of precipitation data, glacier mass balance data and calibration parameters. In general, the WASA model simulates stronger snow and glacier melt in the near future than the SWIM-G model, and it leads to a faster glacier retreat. As a result, there is less glacier storage available and less glacier melt occurs in the WASA simulations for the medium and far future. More detailed discussion on these two models is available in Wortmann (2017).

The lack of sufficient observed discharge data (spatially and in time) makes the calibration and validation procedure for the lowland area complicated as well. The models for all headwaters could be calibrated and validated only for periods before 1987/1988, but the SWIM-oasis model had to be validated in 1990s when the better quality water abstraction data was available. The simulation error at Alar is caused by

headwater and the oasis model as well as abstraction data. However, it is impossible to attribute these errors without better information on observed discharge and abstraction amount.

There was also lack of irrigation data for such a large-scale study. We had only the irrigation instructions for the Aksu basin, and assumed that the irrigation quota and schedule for the Awati County could be also applied for the Hotan and Yarkand basins. This assumption is questionable because these three basins have different geographic and climatic conditions. We compared the estimated water demand and the actual water withdrawal from 1989 to 2002 for the Hotan and Yarkand basins, using available data. The biases were −8 and 13%, respectively, which is still acceptable. However, the availability of local irrigation information would increase the robustness of the climate and agricultural impact study in these two basins.

In addition, we should notice that in reality the irrigation quota from the instructions may not match the crop water demand. In this study, we did not aim to evaluate the simulated water demand at a daily time step as well as annual crop yields. In order to better simulate the daily water demand and crop yields, the calculation of irrigation demands using standard approaches would be more appropriate than the method based on irrigation instructions. However, in such a case, the effects of flooding irrigations, especially for soil leaching before sawing and moisture maintenance would be poorly represented, and the simulated discharge could not be directly compared to the government quota.

6. Conclusions

This study presents a first comprehensive analysis of climate and adaptation measures impacts on water resources at Alar, the last gauge of the Upper Tarim River using headwater discharge of two combinations of hydrological models, 28 climate projections and 30 agricultural scenarios. The results provide not only a basis for creating optimal plans of sustainable development for the Upper Tarim River but also valuable information on water availability to the downstream water users. In addition, the study shows that simulation models can serve as tools to provide comprehensive information for local climate adaptation policy making.

The projected results show that the river discharge at Alar is likely to increase in a warmer climate if the agricultural area is reduced to the level as in 1998 without water saving measures. There would be more water under higher RCP forcing scenarios than under the lower ones, due to increased glacier melting and increased precipitation. The agricultural area as in 2010 would directly lead to greater demands of irrigation water and would reduce water availability in the main Tarim River. If the agricultural area as in 2010 is kept in the future, strong water saving measures must be applied to ensure continued water inflow to the Tarim under all climate scenarios. However, if the area continues to expand, a decrease in river discharge in the Upper Tarim at the end of this century under the RCP2.6 scenario can be expected. Hence, the expansion of agricultural area should be strictly controlled or combined with water saving measures that are even stronger than the ones considered in this study.

The uncertainty of the projection results is much larger in the far than in the near future, which is mainly caused by the climate and headwater models in high RCP forcing scenarios. The significant differences in the projections between the two headwater models confirm that the uncertainty from hydrological models should not be ignored in climate impact studies for this region. More and better observation data is required to improve the model parameterization to reduce the overall uncertainty of the model chain. In the lowland area, additional information on discharge and irrigation practices would be helpful to improve the model reliability for simulations in arid regions. Future studies should also consider other potential impacts on the oasis environment and socio-economic issues.

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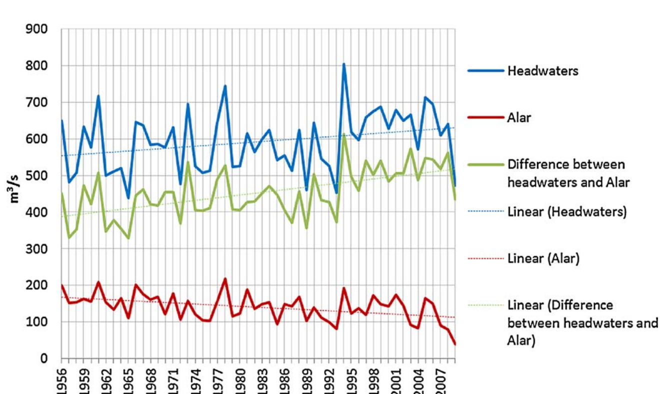
Appendix A. The annual mean discharge from all headwaters and at gauge Alar and their annual differences from 1956 to 2009. The dashed lines show the linear trends of the annual discharges and their differences. (data Source: Gou et al. (2010); Wang (2006) and Deng et al. (2013))



Appendix B. The list of climate projections and their changes compared to the reference in 1971–2000 for each catchment

Basin	GCM/RCM	2011–2040						2041–2070						2071–2099					
		Changes in T [°C]			Changes in P [%]			Changes in T [°C]			Changes in P [%]			Changes in T [°C]			Changes in P [%]		
		RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
Total basin	MRI-CGCM3	0.68	0.82	0.86	14	17	18	0.87	1.45	2.26	20	26	32	1.06	1.91	3.99	24	35	54
	MIROC-ESM	1.62	1.43	1.72	19	19	22	2.31	2.87	3.81	23	31	36	2.40	3.43	6.56	28	37	47
	MIROC-ESM-CHEM	1.91	1.28	1.76	19	19	21	2.24	2.63	4.13	22	30	29	2.24	3.21	6.56	14	33	57
	MIROC5	1.21	1.19	1.34	32	35	40	2.02	2.43	3.24	35	32	48	1.89	3.10	5.04	25	33	65
	IPSL-CM5A-LR	1.54	1.60	1.72	1	−7	−1	1.91	2.71	3.72	−2	−5	−4	2.03	3.24	6.00	5	−4	−5
	HadGEM2-ES	1.99	1.68	1.90	5	4	−1	2.56	3.13	4.25	10	13	14	2.34	4.16	6.85	11	17	34
	GFDL-ESM2M	0.93	0.92	1.21	14	16	10	1.04	1.57	2.08	21	19	30	0.87	1.72	3.35	17	25	27
	CNRM-CM5	0.76	0.90	1.02	15	16	15	1.30	1.50	2.13	15	23	30	1.22	1.98	3.51	22	30	49
	CCLM	0.91	0.83	0.91	10	12	13	1.23	1.70	2.39	10	14	16	0.72	2.08	4.23	13	8	14
Aksu	MRI-CGCM3	0.58	0.79	0.81	10	11	12	0.85	1.37	2.25	13	18	15	1.06	1.87	4.05	21	27	28
	MIROC-ESM	1.76	1.48	1.80	22	17	22	2.37	2.93	3.93	31	30	31	2.48	3.46	6.56	30	38	39
	MIROC-ESM-CHEM	1.89	1.21	1.69	19	18	21	2.22	2.51	3.98	21	27	21	2.22	3.14	6.28	17	32	44
	MIROC5	1.35	1.29	1.39	22	25	30	2.10	2.46	3.46	22	20	27	1.89	3.13	5.14	15	20	35
	IPSL-CM5A-LR	1.63	1.71	1.78	−8	−13	−7	1.99	2.79	3.73	−10	−15	−16	2.14	3.28	5.97	−8	−16	−20
	HadGEM2-ES	1.96	1.67	2.00	1	−1	−9	2.58	3.15	4.34	−2	2	−4	2.22	4.26	7.05	1	3	1
	GFDL-ESM2M	0.80	0.80	1.11	9	11	2	0.86	1.49	1.85	19	11	14	0.73	1.54	3.10	14	17	8
	CNRM-CM5	0.97	1.09	1.16	11	13	12	1.53	1.62	2.38	10	19	22	1.38	2.18	3.92	19	25	33
	CCLM	0.94	0.81	0.83	5	9	9	1.20	1.68	2.35	7	8	8	0.72	2.07	4.19	9	0	2
Hotan	MRI-CGCM3	0.70	0.80	0.85	20	25	25	0.86	1.44	2.19	30	41	56	1.04	1.86	3.85	27	49	91
	MIROC-ESM	1.57	1.43	1.69	13	18	17	2.24	2.79	3.69	14	30	44	2.35	3.37	6.37	26	32	59
	MIROC-ESM-CHEM	1.94	1.36	1.78	19	18	19	2.24	2.69	4.10	24	32	42	2.20	3.22	6.54	13	35	80
	MIROC5	1.14	1.15	1.36	43	50	49	1.97	2.40	3.14	51	49	76	1.93	3.07	4.88	38	57	114
	IPSL-CM5A-LR	1.43	1.45	1.64	13	9	9	1.78	2.56	3.58	15	13	18	1.91	3.10	5.82	23	19	26
	HadGEM2-ES	1.93	1.62	1.79	13	14	11	2.46	3.03	4.08	27	30	40	2.32	4.02	6.59	24	40	84
	GFDL-ESM2M	0.85	0.87	1.14	10	14	15	0.99	1.47	1.98	14	17	45	0.81	1.61	3.23	10	28	40
	CNRM-CM5	0.69	0.84	0.98	23	22	22	1.22	1.54	2.07	24	29	45	1.18	1.92	3.40	31	40	82
	CCLM	0.87	0.84	0.94	11	12	14	1.24	1.68	2.40	12	18	21	0.74	2.06	4.23	13	14	25

Yarkand	MRI-CGCM3	0.73	0.85	0.90	15	22	23	0.89	1.52	2.32	27	31	44	1.07	1.97	4.06	28	38	73
	MIROC-ESM	1.56	1.38	1.70	18	23	25	2.33	2.87	3.83	15	33	39	2.38	3.46	6.72	25	38	53
	MIROC-ESM-CHEM	1.90	1.28	1.79	19	23	22	2.25	2.66	4.25	24	32	36	2.30	3.26	6.78	11	33	64
	MIROC5	1.17	1.14	1.28	43	43	51	2.00	2.43	3.17	47	43	66	1.86	3.09	5.09	34	41	89
	IPSL-CM5A-LR	1.56	1.63	1.75	9	−6	4	1.95	2.75	3.83	1	2	4	2.05	3.32	6.18	16	2	2
	HadGEM2-ES	2.06	1.74	1.93	9	8	6	2.62	3.19	4.32	21	23	28	2.46	4.21	6.92	19	28	62
	GFDL-ESM2M	1.08	1.05	1.35	27	23	21	1.20	1.71	2.32	28	32	48	1.02	1.93	3.63	25	36	50
	CNRM-CM5	0.67	0.81	0.95	15	19	15	1.19	1.39	1.99	17	26	34	1.15	1.88	3.31	21	30	55
	CCLM	0.91	0.85	0.95	17	16	19	1.26	1.73	2.42	13	20	24	0.71	2.11	4.25	18	16	23

Basin	GCM/RCM	2011–2040		2041–2070		2071–2099	
		Changes in T [°C]	Changes in P [%]	Changes in T [°C]	Changes in P [%]	Changes in T [°C]	Changes in P [%]
Total basin	REMO	0.92	12	2.17	28	3.77	16
Aksu		0.98	4	2.19	18	3.9	2
Hotan		0.92	21	2.21	45	3.68	39
Yarkand		0.89	15	2.12	29	3.73	21

Appendix C. The selected 30 combination of agricultural scenarios

Scenario Nr.	Explanation				
	Agricultural area	Crop distribution as in	Conventional irrigation efficiency	Drip irrigation ratio [%]	Reduction of river transmission losses [%]
$A_0C_0E_0D_0R_0$	as in 1998	1998	as in 1998	0	0
$A_1C_0E_0D_0R_0$	as in 2010	1998	as in 1998	0	0
$A_1C_1E_0D_0R_0$	as in 2010	2010	as in 1998	0	0
$A_1C_0E_1D_0R_0$	as in 2010	1998	0.53	0	0
$A_1C_0E_0D_1R_0$	as in 2010	1998	as in 1998	25	0
$A_1C_0E_0D_0R_1$	as in 2010	1998	as in 1998	0	15
$A_1C_1E_1D_0R_0$	as in 2010	2010	0.53	0	0
$A_1C_1E_1D_1R_0$	as in 2010	2010	0.53	25	0
$A_1C_1E_1D_1R_1$	as in 2010	2010	0.53	25	15
$A_1C_1E_2D_1R_1$	as in 2010	2010	0.57	25	15
$A_1C_1E_1D_2R_1$	as in 2010	2010	0.53	50	15
$A_1C_1E_1D_1R_2$	as in 2010	2010	0.53	25	30
$A_1C_1E_2D_2R_1$	as in 2010	2010	0.57	50	15
$A_1C_1E_1D_2R_2$	as in 2010	2010	0.53	50	30
$A_1C_1E_2D_1R_2$	as in 2010	2010	0.57	25	30
$A_1C_1E_2D_2R_2$	as in 2010	2010	0.57	50	30
$A_2C_0E_0D_0R_0$	further increase	1998	as in 1998	0	0
$A_2C_1E_0D_0R_0$	further increase	2010	as in 1998	0	0
$A_2C_0E_1D_0R_0$	further increase	1998	0.53	0	0
$A_2C_0E_0D_1R_0$	further increase	1998	as in 1998	25	0
$A_2C_0E_0D_0R_1$	further increase	1998	as in 1998	0	15
$A_2C_1E_1D_0R_0$	further increase	2010	0.53	0	0
$A_2C_1E_1D_1R_0$	further increase	2010	0.53	25	0

$A_2C_1E_1D_1R_1$	further increase	2010	0.53	25	15
$A_2C_1E_2D_1R_1$	further increase	2010	0.57	25	15
$A_2C_1E_1D_2R_1$	further increase	2010	0.53	50	15
$A_2C_1E_1D_1R_2$	further increase	2010	0.53	25	30
$A_2C_1E_2D_2R_1$	further increase	2010	0.57	50	15
$A_2C_1E_1D_2R_2$	further increase	2010	0.53	50	30
$A_2C_1E_2D_1R_2$	further increase	2010	0.57	50	30
$A_2C_1E_2D_2R_2$	further increase	2010	0.57	50	30

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